DESIGN AND PERFORMANCE OF A ONE-HALF MV REP-RATE PULSER *

A. Ramrus, S. Eckhouse, R. Hamm, N. C. Jaitly, W. Richardson, and G. Schofield

Maxwell Laboratories, Inc.
8888 Balboa Avenue,
San Diego, California 92123

and

T. Cavazos, H. Dave Singh, and S. Levy

U.S. Army LABCOM-ETDL
Pulsed Power Center
Fort Monmouth, New Jersey

Abstract

A rep-rate pulser system is under development for use as an Army user facility This pulser is entering its final stages of testing prior to delivery. This paper presents results which show the pulser's performance demonstrated to date and describes future upgrades now in progress. The pulser system contains a power supply which energizes a resonant charging circuit which charges a PFN to 1 MV. This power supply can provide up to 300 kW in one second bursts to the pulser. The output of the power unit charges the pulser's 10.5 μF primary capacitor bank to 80 kV in 5 ms. This bank is then discharged into the primary of a 1:13.5 iron-core pulse transformer. The transformer's core is reset by the charging current to the 10.2 μF capacitor bank. A pair of low inductance, simultaneously triggered gas switches discharges the capacitors into the primary winding of the transformer. The transformer secondary resonant-charges a 5 Ω PFN to 1 MV in 7 μs. The stored PFN energy is thus 28 kJ. A single self-breaking output switch discharges the PFN into a low inductance 5 Ω load resistor. The pulser section, extending from the primary capacitors to the resistive dummy load is contained within an oil tank. The pulser was tested in single pulse and low rep-rates. The specified 500 kV load voltage was achieved without breakdown or corona. A 10 to 90% risetime of approximately 30 ns was obtained. The pulsewidth of the flat-top, a critical parameter for this pulser, was 450 ns (within an amplitude range ±5% of peak). The pulser and power sections are interfaced to a Macintosh IIcx computer. This computer accepts commands while operating under the LabVIEW software system which allows the pre-setting of all required pulser settings, including rep-rate, number of shots, burst width and the amplitude and timing of voltages and currents within the power unit. The LabVIEW control program also incorporates fault detection and display routines.

Introduction

The specifications on pulsers for loads of military interest are primarily dependent on the technical requirements. Plasma and e-beam loads now under study have impedances in the 10s of ohm range but with further development, expectations are that impedance will be reduced as the output peak power increases. Pulser impedances below 10 Ω are anticipated. In general terms, one approach to attaining higher peak power and lower impedance is to use pulses with relatively short pulsewidth. In this regard, pulsers with pulsewidths of ~0.5 μs are under study. This paper describes a 5 Ω, 500 kV pulser. This pulser was intended (1) to serve as a reliable user facility for a wide range of loads and (2) to be a prototype for more compact and lightweight pulsers to be developed in the future. Thus to meet user requirements on reliability, and to construct a pulser with only limited investment in development, an oil insulated, transformer-based pulser was constructed with the specifications shown in Table 1. These specifications were established by the Army's Harry Diamond Laboratory (HDL) and the Electronics Technology and Devices Laboratory (ETDL).

Table 1. Pulser Specifications.

Output Voltage	500 kV
Pulser Impedance	5 Ω
Pulse Width (flat-top)	450 ns
Max. Rep-rate	7 Hz
Pulse Risetime	< 50 ns
Pulse decay time	< 100 ns
Burst Power	300 kW for ~1 s
Nominal burst length	1 s
Pulse Energy	30 kJ

At this writing, the pulser has successfully undergone full voltage testing at rep-rates up to 3 Hz. Documentation and final testing are in progress. The originally specified rep-rate of 7 Hz would be attainable with the addition of power conditioning components in the AC portion of the command charging system, although the installation and test of these components is not planned at present. Further exploratory work is in progress on a solid-state end-of-line clipper to be discussed later in this paper.

System Description

The pulser consists of a capacitor bank which is gas switched into the primary of an iron-core pulse transformer (manufactured by Stanganese Industries, Inc.) The output of the transformer resonantly charges a PFN to 1 MV, at which time an output switch self-closes, discharging the PFN into the output load. For the present, this output load is a set of four paralleled resistors but in its future use, the output switch will be connected directly or through resistors to the load. The pulser is energized from a power system capable of providing up to 380 kW for ~1 s. The system is controlled with a Macintosh IICX computer operating with LabVIEW software. A block diagram is shown in Figure 1.

*This work was funded by the U.S. Army LABCOM Harry Diamond Laboratories under Contract to ETDL, Contract Number DAAL01-89-C-0901.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1991**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Design And Performance Of A One-Half Mv Rep-Rate Pulser**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Medical Equipment Group, Varian Associates 911 Hansen Way, Palo Alto, CA 94303**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT
A rep-rate pulser system is under development for use as an Army user facility This pulser is entering its final stages of testing prior to delivery. This paper presents results which show the pulser's performance demonstrated to date and describes future upgrades now in progress. The pulser system contains a power supply which energizes a resonant charging circuit which charges a PFN to 1 MV. This power supply can provide up to 300 kW in one second bursts to the pulser. The output of the power unit charges the pulser' s 10.5 IJ.F primary capacitor bank to 80 kV in 5 ms.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

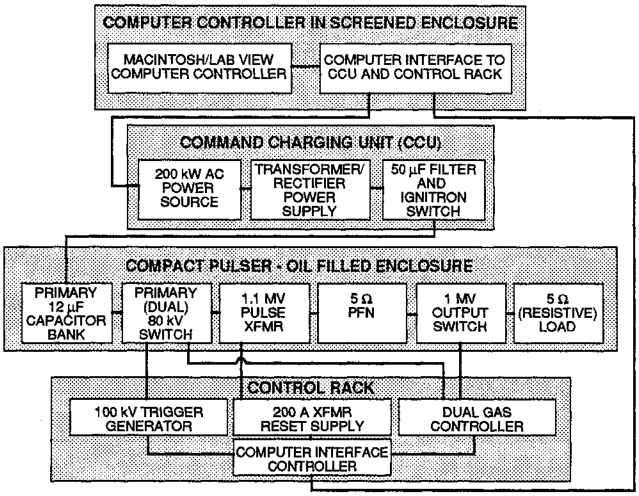

Figure 1. System block diagram

Input Power

The AC power available for this pulser consists of 480 V service capable of providing 200 A for time periods of approximately 1 s. This powers a 60 kV transformer/rectifier power supply. These components constitute the Command Charging Unit, as shown in Figure 2. This system, although not

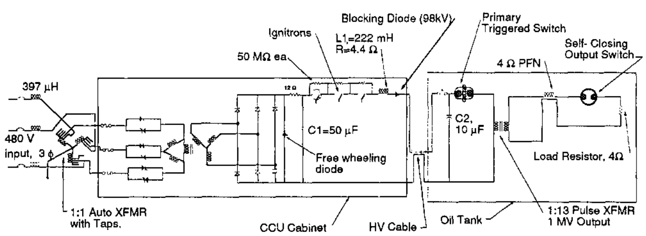

Figure 2. Equivalent circuit of command charging unit and pulser

ideally suited for this compact pulser, was available from a previous program and was adapted to these requirements. For operation at full voltage, the output of the power supply maintains the 50 kV charge voltage on the 50 µF filter bank. When the ignitrons are fired, this filter bank is switched into a 10.2 µF primary capacitor bank through a 222 mH inductor and the primary bank resonantly charges to 80 kV. The charging current waveshape is a half-sine with peak current of 300 A and basewidth of 4.2 ms, as shown in Figure 3. This process

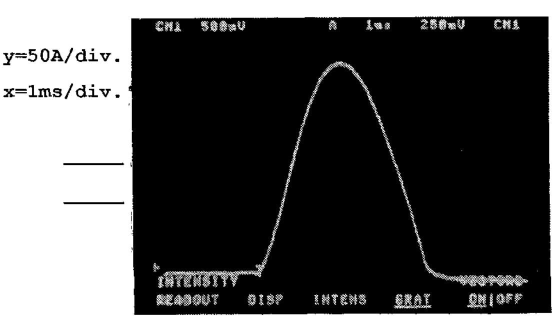

Figure 3. Charging current waveform from filter bank to primary capacitor bank, measured with a Pearson current monitor.

removes 35 kJ from the 50 µF filter bank (which stores 62 kJ at 50 kV) and reduces its voltage to 33 kV. The filter bank voltage is then brought back to the full voltage of 50 kV in less than 100 ms. Thus the power system would be capable of 10 Hz operation, although for only for short bursts, under 1 s.

Pulser

The pulser energy of 32.6 kJ is initially stored in a bank of four 2.55 µF, 80 kV capacitors. The four capacitors are connected in two pairs where each pair is connected in parallel with low inductance buswork. Each pair is connected to a triggered gas pressurized, gas purged, spark-gap. With nearly simultaneous triggering of these two spark gaps, circuit inductance is less than 175 nH. This is compared to the transformer's leakage inductance, referred to the primary, of approximately 900 nH. Low primary inductance is desirable because it minimizes the pulse-charging time of the PFN, and thus, the transformer's core volume. It also reduces the likelihood of breakdown in the PFN. The pulser layout is shown in Figure 4, and the pulse transformer specifications are shown in Table 2.

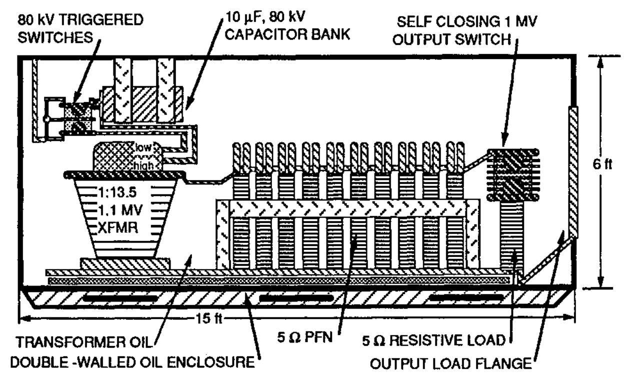

Figure 4. Compact pulser layout, side view

Table 2. Pulse transformer specifications.

Peak Output voltage	1.1 MV
Leakage Inductance (ref. 2nd)	160 µH
Primary Voltage	80 kV
Step-up ratio	1:13.5
Rep-Rate	7 Hz
Secondary Winding Capacitance	< 90 pF
DC Reset current:	~100 A

The primary capacitors were connected to the transformer's primary winding in a configuration which caused the capacitor's charging current to pass through the primary in a direction opposite that of the normal discharge. Thus, recharging the capacitors with the half-sine peak current of 300 A and a basewidth of 4.2 ms, also tends to reset the core. This was done to eliminate the need for a separate dc power supply and isolation inductor. However, when this circuit was used, shot-to-shot variation in transformer output current was observed and dc reset was found to be preferable.

The transformer output is connected to a PFN which contains the total capacitance of 56 nF. This PFN consists of four 20 Ω modules all connected in parallel. Thus, in future operation, one or more modules may be removed from the tank and the pulser impedance adjusted upwards in steps of 20 Ω. Also, it is feasible to connect the modules in series for extended pulsewidth. In all tests to date, the four PFNs were connected in parallel.

Each module contains 10 cells, each consisting of one 1.4 nF capacitor and one 150 nH inductor. The PFN capacitors are double-ended, and have plastic-cases 22 in. long and 4 in by 6 in cross-section. Due to the conservative winding design and the generous capacitor length, the capacitors are capable of 1.3 MV charge voltage although they have been used only to 1 MV in this program. The PFN inductors are fabricated from copper pipe in a square configuration. Careful adjustment of the inductor size and the proximity of one inductor to another was needed in order to optimize the coupling coefficient, which was set at 0.13. Inductor coupling influences the duration of the flat top and that of the pulse tail. This is especially important for PFNs whose capacitors have significant leg inductance compared to the external cell inductance, which is the case in this PFN. The 0.13 coupling coefficient was found to provide the best compromise between pulsewidth and pulse shape for this PFN.

During the transformer's output pulse, the PFN resonantly charges towards the peak voltage of 1.1 MV, while a gas output switch insulates the PFN from the 5 Ω output load. This gas switch self-fires at 90% of Peak (1 MV) which discharges the PFN into the output load.

Computer Controls

The control system is operated with a Macintosh II computer with LabVIEW software. This provides an interactive control system that allows the presetting of system parameters. Therefore the computer controls all key parameters which are: the filter bank charge current waveshape, ignitron firing time, system rep-rate, number of shots, trigger timing, gas flow control to both the primary and the output switches, and control of the reset power supply. Also, the computer shuts down the system in the event of prefire, over or under voltage, over current, or the interruption of interlocks. Of particular importance is the filter bank charging current control. This is accomplished with a computer-based waveform generator which allows the gate pulseshape to the SCRs to be preset. In that way the SCR output current which recharges the filter bank is made approximately constant which prevents damage to the SCRs.

Operating Performance

The triggering time of the primary switches relative to that of the CCU's ignitrons is preset within the computer program prior to initiating a pulse sequence. Since the charging time to charge the 10.2 μF primary capacitors from the filter bank is approximately 4.2 ms, the primary switches are fired 5 ms after the ignitrons are fired. A diode in the pulse charging circuit between the filter bank and the primary bank holds the dc charge on the primary capacitors after charging.

One 100 kV rack-mounted trigger generator triggers both primary switches simultaneously. The trigger lead extends inside the oil tank and is connected to a midplane on each switch. Three 2 nF "door knob" capacitors isolate the trigger lead from the midplane. The midplane is held at the V/2 potential with balancing resistors. In each switch a 1 MΩ resistor extends from the midplane to the charged electrode and one extends to the grounded electrode. Initially, a 10 MΩ resistance was used instead of 1 MΩ but then the switches tended to prefire. This was caused by the excessive RC charging time of the midplane where R is the paralleled resistance of the two balancing resistors and C is the trigger capacitance (~0.7 nF). If the midplane's RC-time is excessive, the midplane is, in effect, triggered due to the potential imbalance and this was corrected by reducing each resistor to 1 MΩ. The switches were found to reliably trigger with a jitter of less than 10 ns. This was determined by connecting a resistive divider to each of the low voltage (grounded) electrodes of the two spark gaps.

A typical charging current from the pulse transformer is shown in Figure 5 and the charging voltage waveshape on the PFN is shown in Figure 6. Also an output voltage across the 5 Ω resistive load is shown in Figure 7.

y=2kA/div.

x=1μs/div.

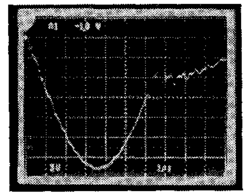

Figure 5. Secondary current waveshape from pulse transformer measured with Pearson probe. Transformer low voltage secondary lead to ground passes through Pearson current sensor 110A.

y=240kV/div.

x=1μs/div.

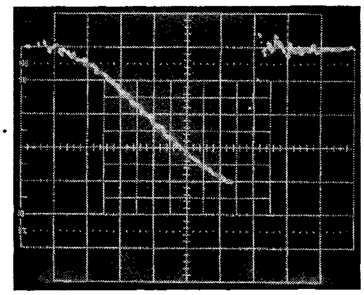

Figure 6. Pulse charging voltage waveshape on the PFN, measured with aqueous copper sulfate resistive divider connected between PFN output electrode and ground.

y=120kv/div.

x=0.1μs/div.

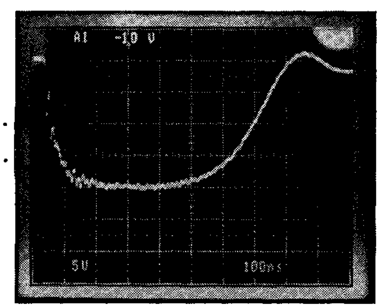

Figure 7. Output voltage waveshape across the 5 Ω output load measured with aqueous copper sulfate resistive divider between load HV terminal and ground.

End-of Line Clipper Tests

An important property of the PFN capacitors used in this program is that their life expectancy is reduced if they are subject to severe reversal. That vulnerability to reversal is a consequence of using relatively highly stressed windings in order to attain MV capability in a capacitor of modest dimensions. In its role as a pulser for a variety of applications, it is expected that some of these sources will undergo short-circuit during the pulse and this can introduce full reversal at the end of the PFN farthest from the load if there is no circuit protection. For high impedance loads (relative to 5 Ω) the pulser can be equipped with series resistors which would reduce reversal under these conditions. For loads which approximately match the pulser, the best protection is to install an end-of-line clipper (EOLC) network at the farthest point from the load.

Maxwell is investigating the feasibility of using solid state diodes to meet this requirement. This concept calls for a set of four EOLC networks, one for each 20 Ω PFN module. Each EOLC would be equipped with a diode stack capable of supporting the inverse voltage of 1 MV and, also, each would have series resistors totaling 20 Ω interspersed within the stack. The waveshape requirements call for the stack to withstand a 1 MV inverse voltage pulse with pulsewidths of 5 μs, followed immediately by a 25 kA fast rising current spike of 25 kA (corresponding to 500 kV/20 Ω). These requirements are severe but diodes manufactured by International Rectifier (IR) show promise of meeting them. Advanced diodes have been under development for some time due to the requirements of various Army rail gun programs and diode elements are now manufactured which in theory can meet the specifications.

To establish diode performance, Maxwell developed a circuit to test the diodes with the appropriate inverse voltage waveshape and forward current spike. This circuit is shown in Figure 8. Consider the left-hand portion of the circuit. This consists of a dc charged capacitor which is switched into a second capacitor through an inductor. In operation, the left hand portion provides the inverse voltage. It does so after closure of switch 1 which creates a resonant waveform on capacitor 2 and also on the diode under test. The charge voltage can be controlled to limit the peak diode voltage to the diode specification. For these tests, IR provided Maxwell with diodes for test and evaluation which consisted of a series-stack of three 5 kV junctions. The circuit parameters were setup accordingly.

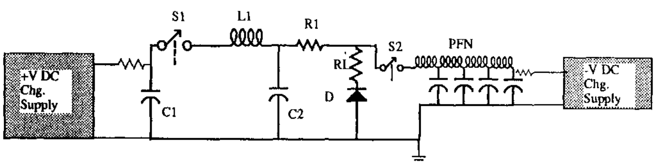

Figure 8. Circuit which simulates voltage and current in the end-of-line-clipper.

The right hand portion of the circuit consists of a low inductance capacitor bank and spark gap, both dc charged to a voltage opposite that of the voltage generator discussed above. When this switch is closed, this bank provides a forward current spike up to 25 kA. When the complete circuit is operated, the voltage generator is dc charged positively, and the current generator is dc charged negatively. When the start switch (shown in the left-hand portion of the circuit diagram) is fired, the resonant voltage appears across the diode (in the inverse direction) and also across the output switch of the current generator. The latter then fires due to the severe overvoltage caused by the sum of the two voltages. The firing point of the current generator's switch can be adjusted with pressure to attain breakdown near the peak of the applied voltage. Thus the waveform sequence closely simulates that which will occur in practice when the EOLC is first charged to inverse voltage by the pulse transformer and then receives a foreward current pulse due to a short circuit in the output load. The diode voltage is shown in Figure 9. Note the voltage spike which appears after the resonant charging portion; this spike is effectively the load voltage (across R2) since the diode is conducting and is caused by the forward current spike.

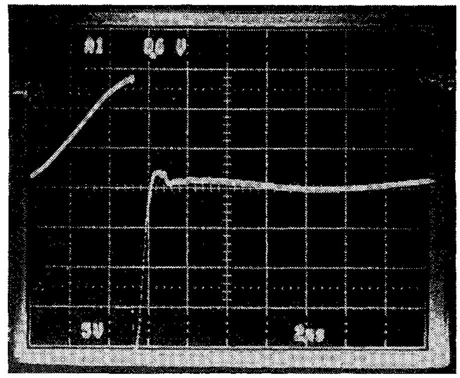

Figure 9. Voltage waveshape from Morganite resistive divider connected from diode to ground, showing inverse applied voltage followed by forward current spike (negative transient through R2) Horizontal Scale: 2 μs/major division, Vertical Scale: 5.5 kV/major division. Peak Voltage: 15.2 kV.

The total of six diode stacks were provided by IR. The first set of three were tested in the simulator and failed early in the test sequence, below the specified values. Analysis of the failures and the applied waveshapes lead to the conclusion that the 25% reversal in the current waveshape generator was probably responsible for the failure. The current source inductance was then reduced in order to provide less than 9% reversal. The second set of tests were then conducted on three new diodes stacks with substantially better results. The diodes now survived approximately 15 shots at full voltage and current at which point two of the three failed. Diode life at lower levels appeared to be extensive but was not tested.

These test results suggest that the diodes can be safely used at operating levels below the specified maxima. For example, an estimated safe level would be 3.5 kV per element, with peak current limited to 20 kA. Most importantly, current and voltage reversal must be minimized. With those precautions, a solid state EOLC meeting the compact pulser's requirements is feasible and with appropriate selection of resistance in the EOLC, the circuit parameters required for extensive diode life can be attained.

Reference

G.N. Glasoe and J. V.Lebacqz, Editors, Pulse Generators, Section 6.3, Dover Publications, 1948

Acknowledgements

The authors wish to thank Richard Doucette for his work on the adaptation of the LabVIEW software to the ETDL system. Also, we wish to thank, James Gosse and Terry Houston for their work on the PFN fabrication and the system integration, respectively.